Charged current π^+ to quasi-elastic cross section ratio in MiniBooNE

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MiniBooNE Motivation

The Liquid Scintillator Neutrino Detector (LSND) observed an excess of electron anti-neutrinos from a muon anti-neutrino source.

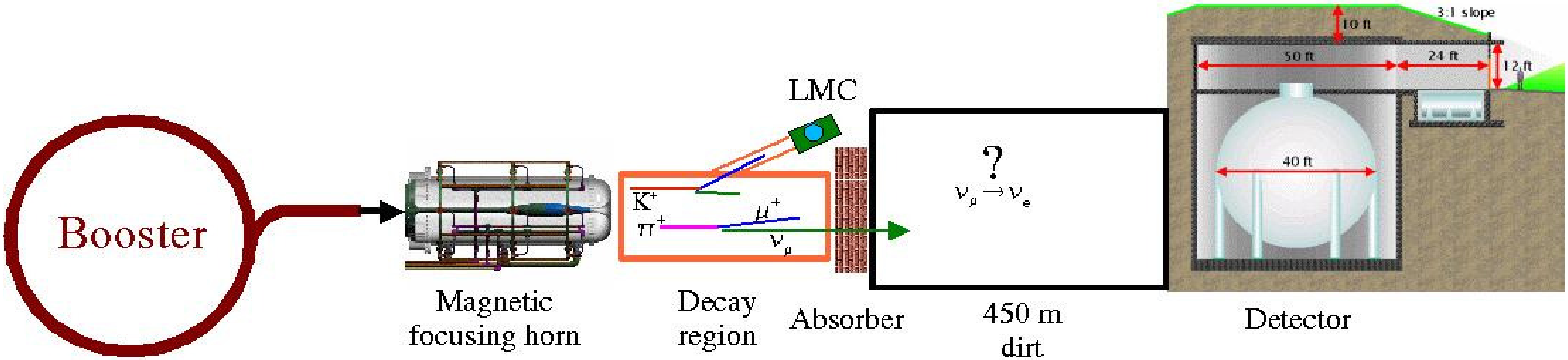
Interpreted as oscillations due to 2-neutrino mixing, this implies a mass splitting of $\Delta m^2 \sim 1\ eV^2$.

But with three known neutrinos, only two independent mass differences are possible. Two are already well-known: $\Delta m^2_{atm} \sim 2x10^{-3}\ eV^2$ and $\Delta m^2_{sol} \sim 7x10^{-5}\ eV^2$. These obviously cannot be made to add up to $1\ eV^2$.

MiniBooNE was designed to confirm or refute this puzzling result, probing the same physics as LSND but with very different systematics.

	LSND	MiniBooNE
L	30 m.	451 m.
E (peak)	40 MeV	800 MeV
Neutrino flavor	Muon anti-neutrinos	Muon neutrinos
Detector	Liquid scintillator	Oil Čerenkov

MiniBooNE Overview



FNAL Booster delivers 8 GeV protons to the beamline.

Protons collide with beryllium target, producing pions and kaons.

Magnetic horn focuses positively charged kaons and pions.

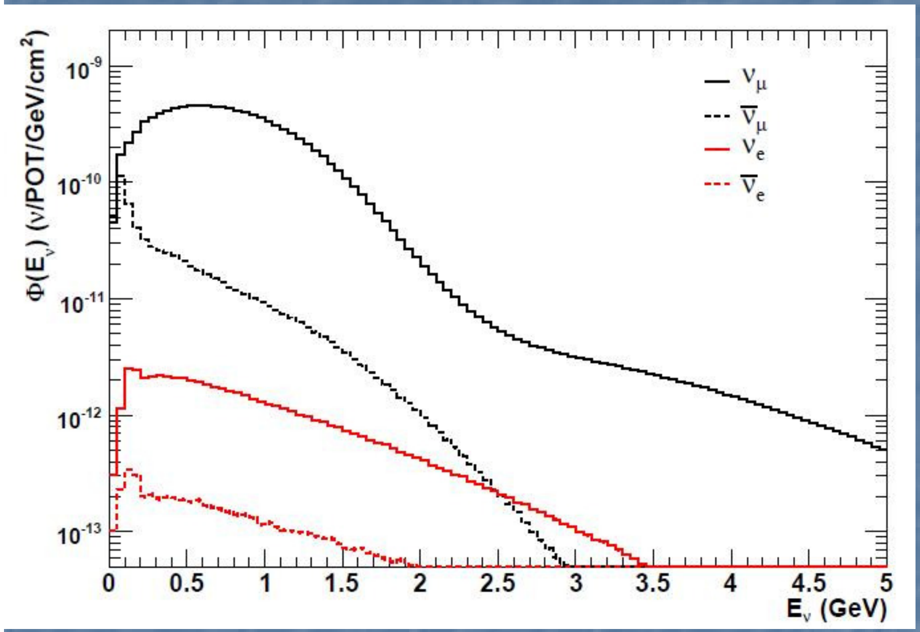
These mesons decay, producing neutrinos.

Other products are stopped in the absorber or in the dirt before reaching the detector.

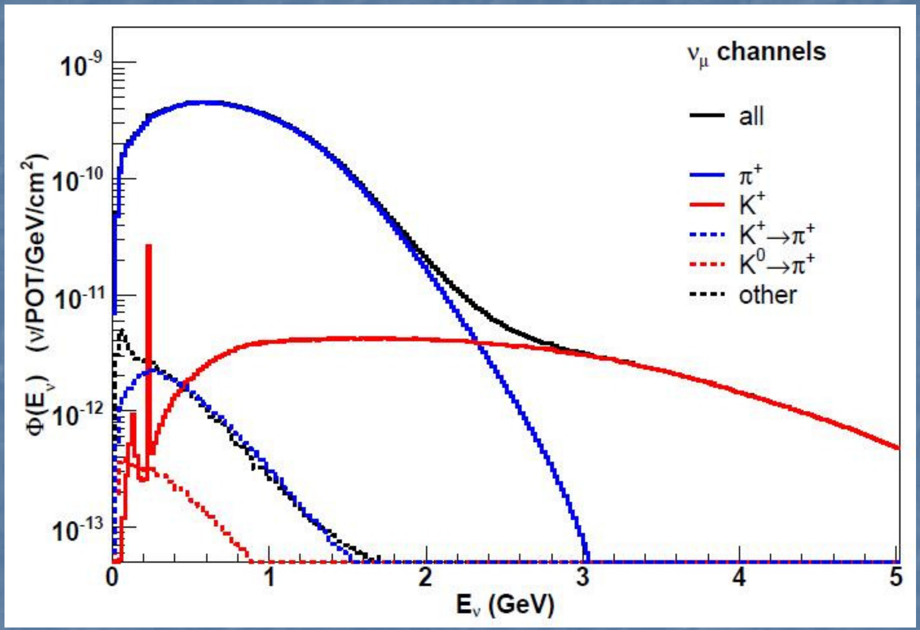
Neutrino Flux

Geant4-based Monte Carlo used to simulate p-Be interactions and subsequent meson decay

Customized model for pion production based on E910 and HARP data



Neutrino flux at MiniBooNE by neutrino species



ν_μ Flux at MiniBooNE by parent meson

93.6% muon neutrino
5.9% muon anti-neutrino
0.5% electron neutrino
< 0.1% electron anti-neutrino

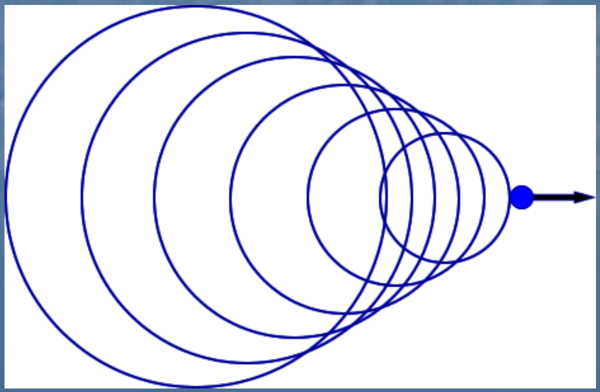
97% of neutrinos from π^+ decay

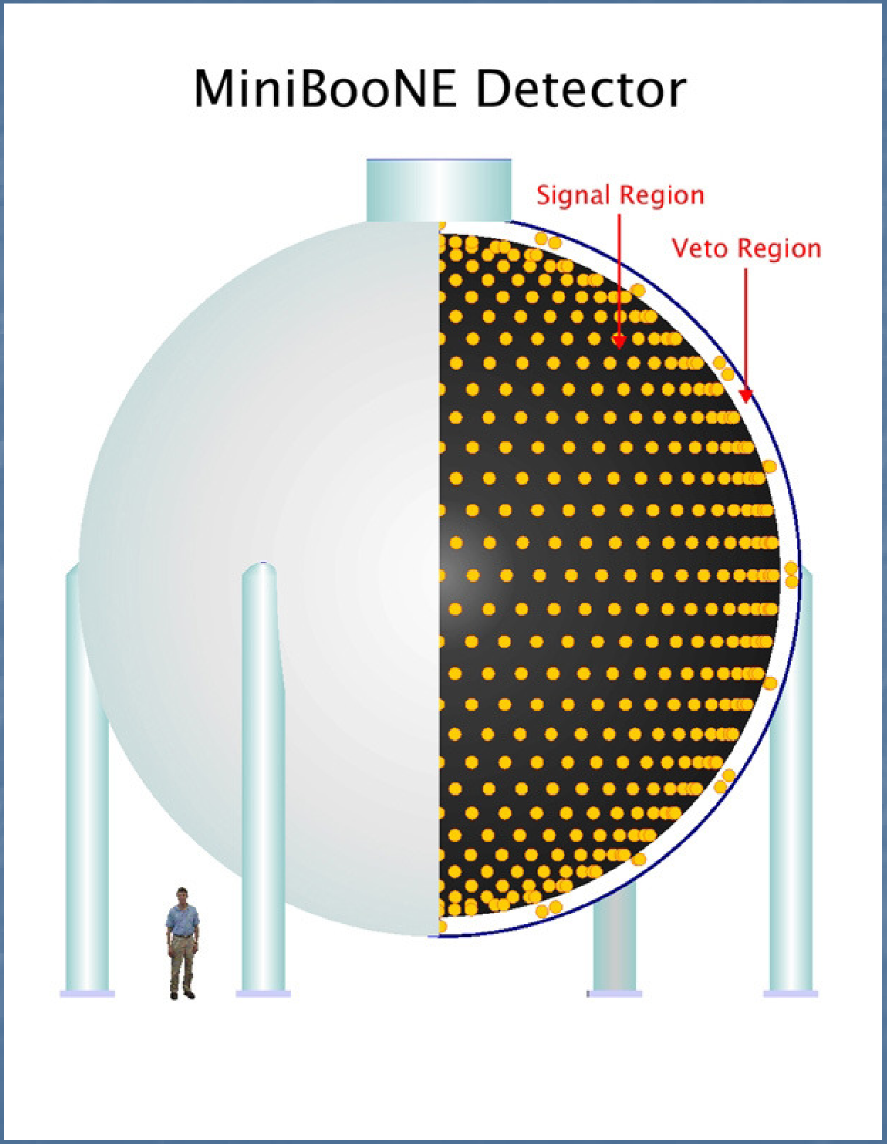
MiniBooNE Detector

- 12 m. diameter spherical tank
- Filled with 800 tons of mineral oil (CH_2)
- Active region lined with 1280 PMTs
- Outer veto region with 240 PMTs

Charged particles in the detector produce mainly Čerenkov light, with a small fraction of light from scintillation.

Čerenkov radiation is analogous to a sonic boom; it occurs when a charged particle is moving faster than the speed of light in the medium.

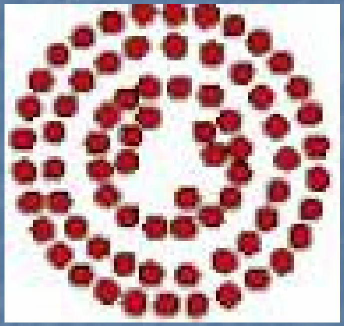




Particle Detection and Identification in MiniBooNE

Electron: Scatters multiple times and stops after travelling a short distance. → Thin, fuzzy ring

Muon: Little deflection; long, straight track → Filled in ring



Our fitters identify time-separated "sub-events", characterize them as electron-like or muon-like, and perform a maximal likelihood fit for the kinetic energy and direction of the particle's track.

Sub-event: a cluster of PMT hits with no more than 10 ns between hits.

Each sub-event typically corresponds to one reconstructable particle track.

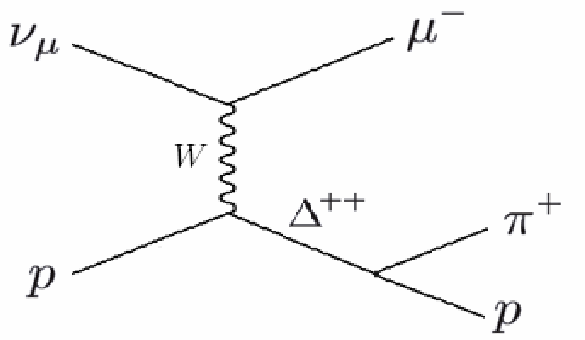
Charged Current Single π^+ (CCπ^+) Events in MiniBooNE

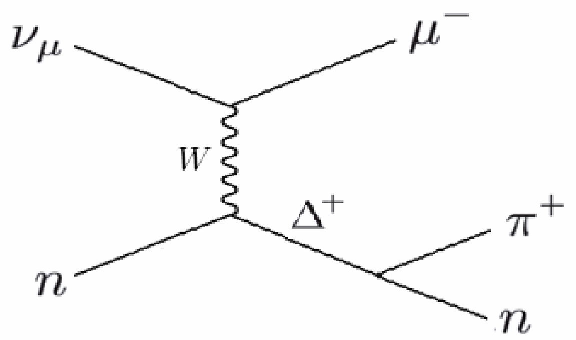
CCπ^+ Resonant

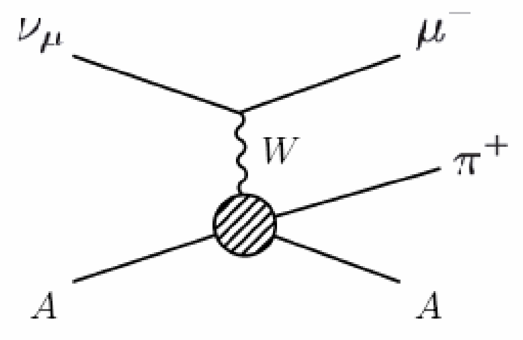
$$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- p \pi^+$$
$$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- n \pi^+$$

CCπ^+ Coherent

$$\nu_\mu A \to \mu^- A \pi^+$$

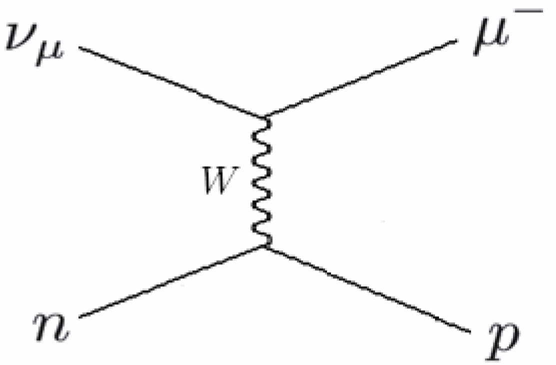






CCQE

$$\nu_\mu n \to \mu^- p$$



We expect about 24% of neutrino events to be CCπ^+ and 40% CCQE.

Of the CCπ^+ events, less than 10% are expected to be produced coherently.

Why do we care about CCπ^+ ?

From a neutrino physics perspective:

CCπ^+ events are very abundant at energies used in oscillation experiments.

In many detectors (e.g. MiniBooNE) CCπ^+ events can look like CCQE.

Thus CCπ^+ is a major background in many oscillation studies.

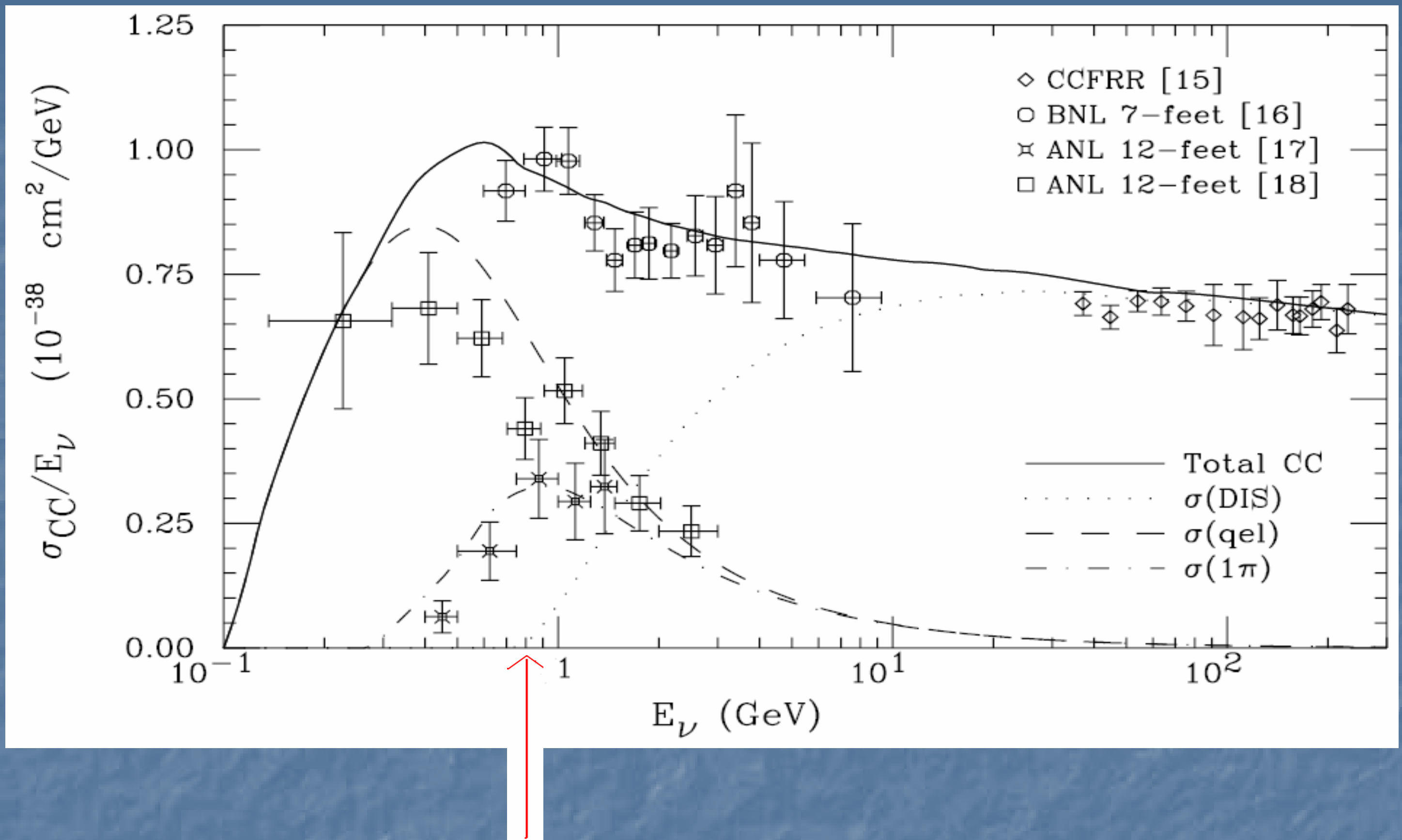
From a nuclear/hadronic physics perspective:

CCπ^+ interactions can offer insight into the mechanisms of both resonant and coherent pion production.

Until recently, only data available was from low-statistics experiments from the 1980s.

Cross section results can help to test our modelling of intra-nuclear final state interactions.

Why Study CCπ^+ in MiniBooNE?



Lipari et al., Phys. Rev. Lett. 74, 4384 (1995)

MiniBooNE has collected the world's largest sample of CCπ+ events.
High statistics allow us to achieve a very pure sample.
Energy range is of interest for both ν_μ disappearance and ν_e appearance searches.

$CC\pi^+$/CCQE Analysis

Cross section ratio = ratio of true number of $CC\pi^+$ to CCQE events in detector

Measure number of events passing cuts in each energy bin.

Need to correct number of events passing ($CC\pi+$, CCQE) cuts to true number of ($CC\pi+$, CCQE) events

Use Monte Carlo to obtain corrections for each sample and use these to correct the raw numbers of events passing cuts.

f = signal fraction = (signal events passing cuts)/(events passing cuts)

ε = cut efficiency = (signal events passing cuts)/(signal events)

U = Energy unfolding matrix (I'll discuss this in a moment)

$$\frac{\sigma_{ccpip,i}}{\sigma_{ccqe,i}} = \frac{\epsilon^{-1}_{ccpip,i} * \sum_j U_{ij} * f_{ccpip,j} * N_{ccpip-cuts,j}}{\epsilon^{-1}_{ccqe,i} * \sum_j U_{ij} * f_{ccqe,j} * N_{ccqe-cuts,j}}$$

Observed Ratio and Corrected Ratio

Observed ratio: Ratio of $CC\pi^+$-like to CCQE-like events <u>after</u> nuclear interactions.

Includes corrections for re-interactions in the detector.

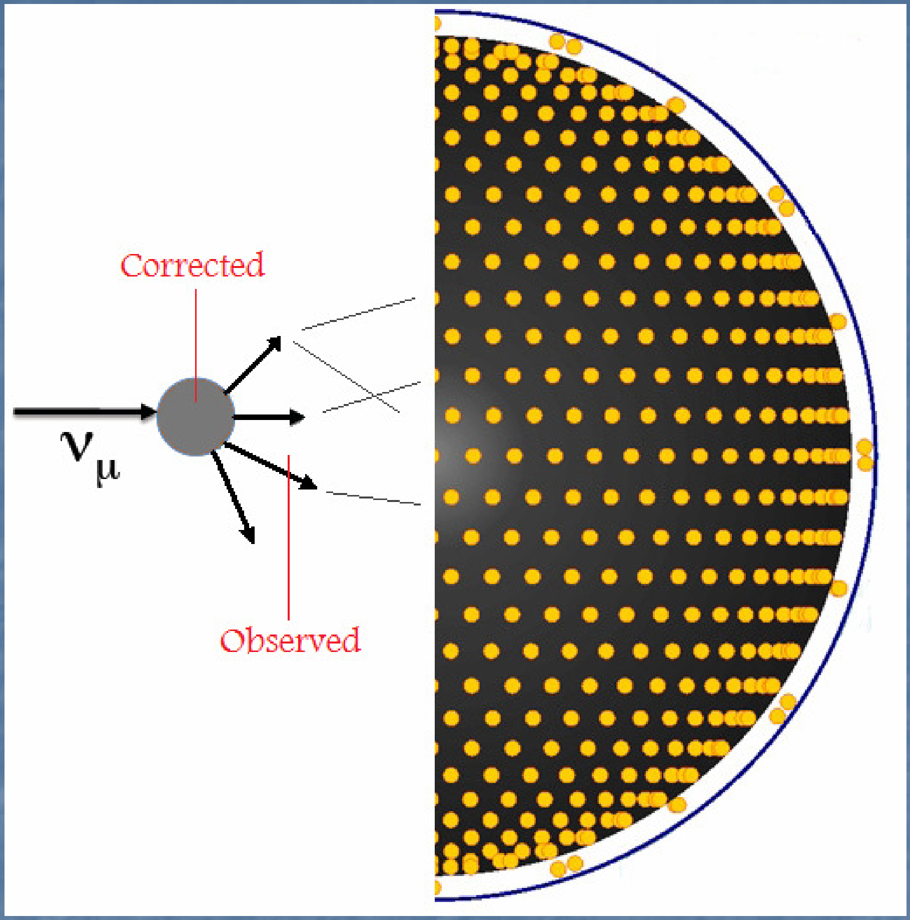
$CC\pi^+$-like:
- One μ^- and no other muons
- One π^+ and no other pions
- No additional hadrons other than protons or neutrons

CCQE-like:
- One μ^- and no other muons
- No hadrons other than protons or neutrons

Corrected ratio: Ratio of $CC\pi^+$ to CCQE events <u>before</u> nuclear interactions.

Includes corrections for re-interactions in the nucleus and in the detector.

More model-dependent, but needed to compare results with previous experiments.



Event Selection

$CC\pi^+$ events are identified by:

1. The outgoing muon
2. The decay electron at the end of the muon’s track
3. The decay positron at the end of the pion’s track

CCQE events are identified by:

1. The outgoing muon
2. The decay electron at the end of the muon’s track

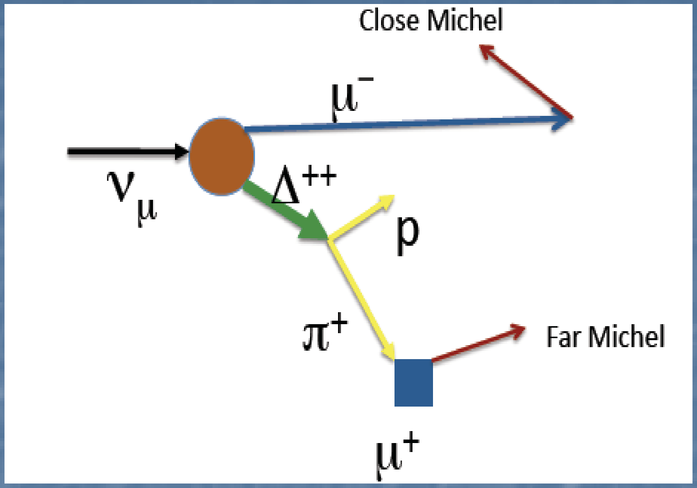
These simple criteria almost completely select our event samples.

Full list of cuts:

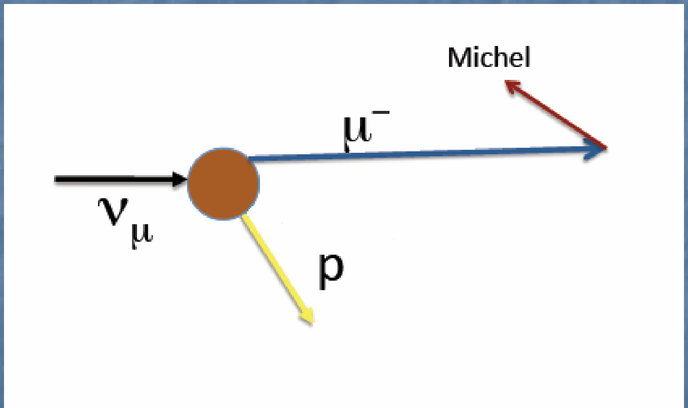
CCQE	$CC\pi^+$
Exactly 2 sub-events	Exactly 3 sub-events
First SE in beam window	First SE in beam window
Veto hits < 6 for each SE	Veto hits < 6 for each SE
Tank hits > 200 for 1st SE	Tank hits > 175 for 1st SE
Tank hits < 200 for 2nd SE	20 < Tank hits < 200 for subsequent SE
Michel distance < 100 cm.	Michel distance < 150 cm.
First SE < 500 cm. from center	All SE < 500 cm. from center

$CC\pi^+$: 12% efficiency
46,649 events

CCQE: 26% efficiency
195,482 events



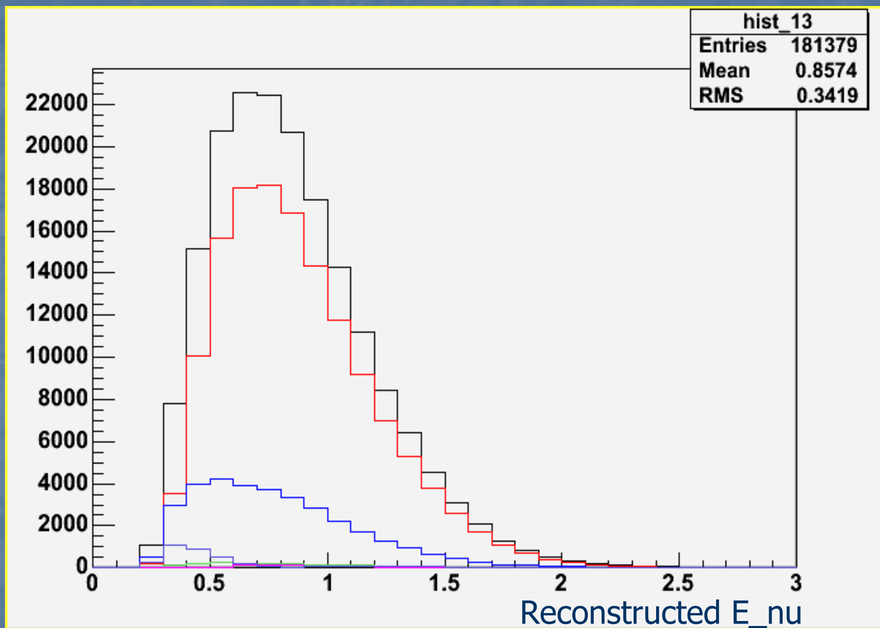
$CC\pi^+$ event



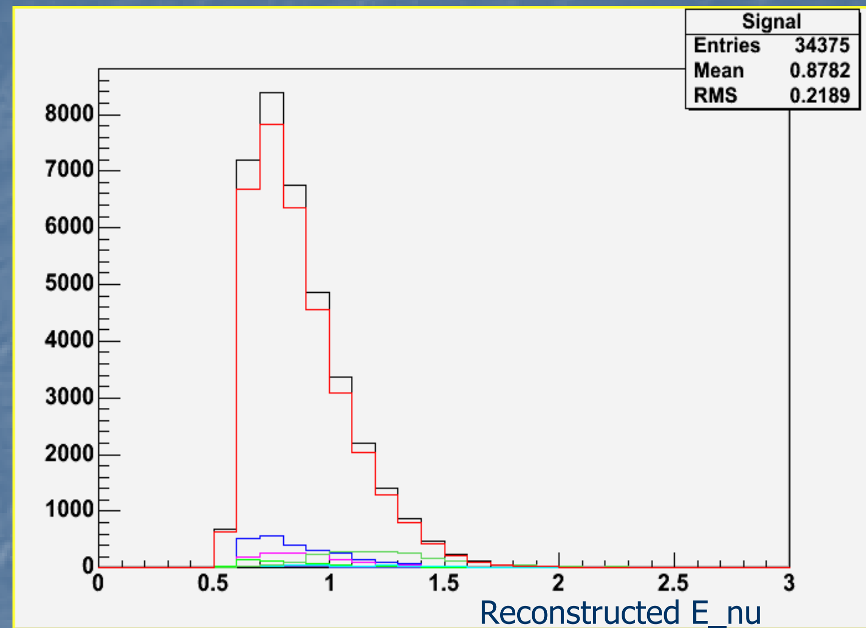
CCQE event

Event Samples

CCQE



CCπ^+



CCQE (red)	72.0 %
CCπ^+ resonant (blue)	18.3 %
CCπ^+ coherent (green)	1.1 %
NCπ^0 (dark purple)	2.0 %
Multi-pion (light purple)	0.5 %
Other	6.1 %

CCπ^+ total	86.8%
CCπ^+ resonant (red)	80.9%
CCπ^+ coherent (dark blue)	5.9 %
CCQE (dark green)	5.2 %
Multi-pion (light purple)	3.8 %
CCπ^0 (light green)	1.5 %
DIS (light blue)	1.0 %
Other	1.6 %

Energy Unfolding

Reconstructed neutrino energy is in general not the same as true neutrino energy due to 'smearing' in reconstruction.

We need to deconvolute or 'unfold' our neutrino energy distributions to obtain physically meaningful quantities.

The first step is easy: perform reconstruction on a Monte Carlo sample and form a 'migration matrix' by comparing true and reconstructed energies event by event.

Obtaining an unfolding algorithm from this migration matrix is trickier.

The standard matrix inversion method presents some notorious problems.

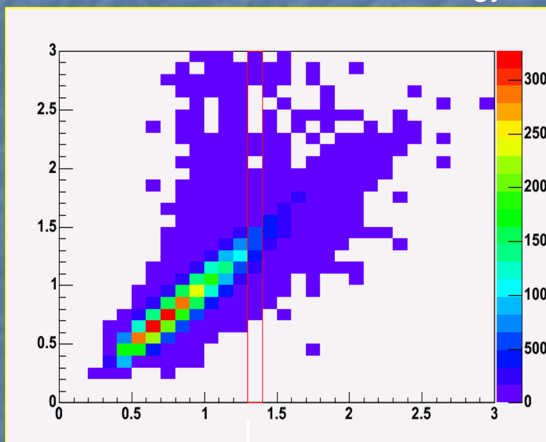
For this analysis matrix inversion was not viable and another technique was needed.

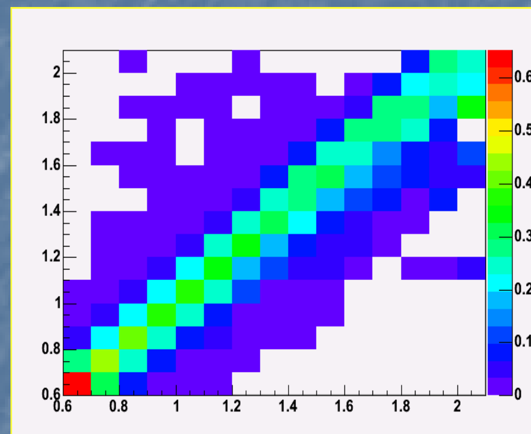
Energy Unfolding

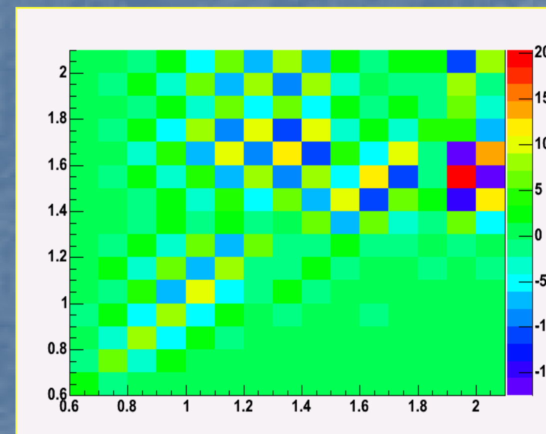
Matrix inversion method

Migration Matrix → Normalize by true energy and truncate → Smearing matrix → Invert → Unfolding matrix

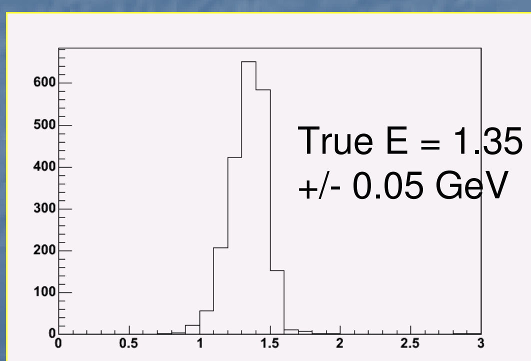
Rec E







↓ True E



Rec E

Approach: For a given true energy, what percentage ends up in each reconstructed bin?

Energy Unfolding

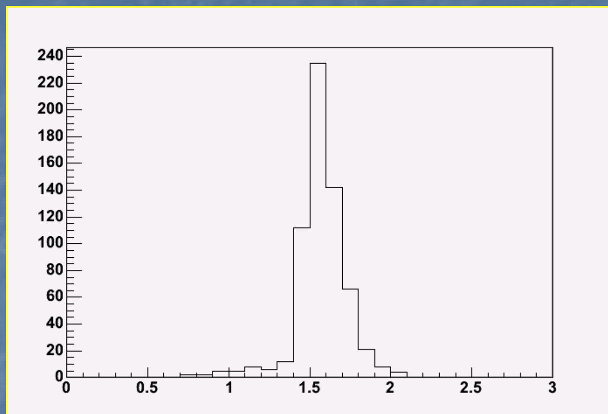
Matrix inversion method

- Mathematically correct ‘solution’ to the unfolding problem
- No bias
- Matrix inversion difficult:
    - Need to truncate histograms or reduce energy resolution to prevent empty columns
    - Inversion still numerically unstable and may fail
- Unsmeared distributions highly sensitive to small perturbations in reconstructed distributions
- When it fails, can give bizarre results (e.g. huge negative values)
- Thus, can introduce large statistical error.

Energy Unfolding

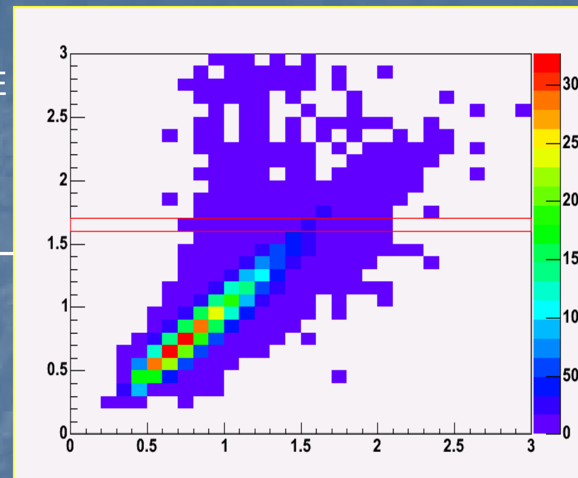
Alternative method

Rec E = 1.65 +/- 0.05 GeV



True E

Rec E



Migration Matrix

True E

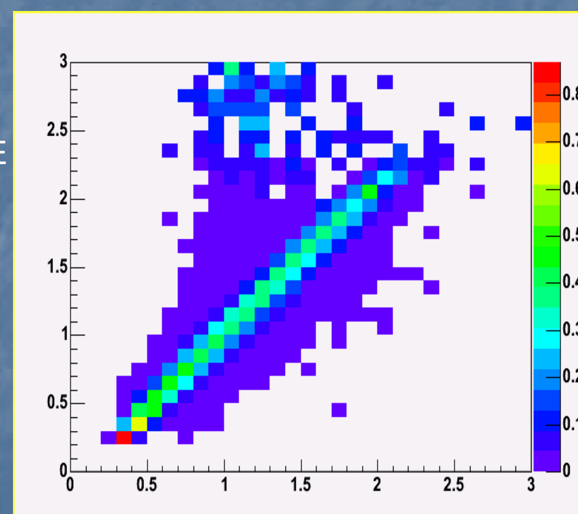
Normalize by reconstructed energy

Approach: For a given reconstructed energy, what percentage came from each true bin?

This turns out to be equivalent to a Bayesian method described in G. D'Agostini, Nucl. Instr. Meth. A362, 487 (1995)

$$
\begin{aligned}
P(T_i|R_j) &= \frac{P(R_j|T_i)P(T_i)}{P(R_j)} \\
&= \frac{P(R_j|T_i)P(T_i)}{\Sigma_l P(R_j|T_l)P(T_l)} \\
&= \frac{M_{ij}}{\Sigma_l M_{lj}}
\end{aligned}
$$

Rec E



Unfolding matrix

True E

Energy Unfolding

Alternative method

- Avoids all the problems of matrix inversion

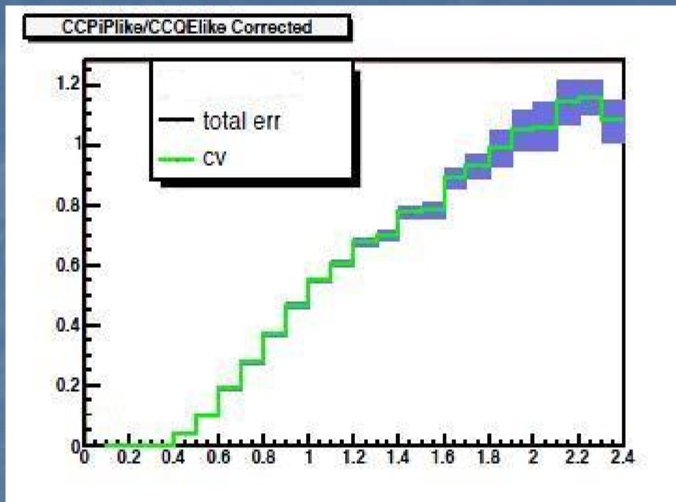
- Not critically dependent on small fluctuations in reconstructed distribution

- No danger of bizarre results

- Introduces bias: unsmearing matrix depends on what true flux you use to construct it.

- Effectively, introduces new source of systematic error.

Systematic Uncertainties



π^+ production

Error matrix calculation

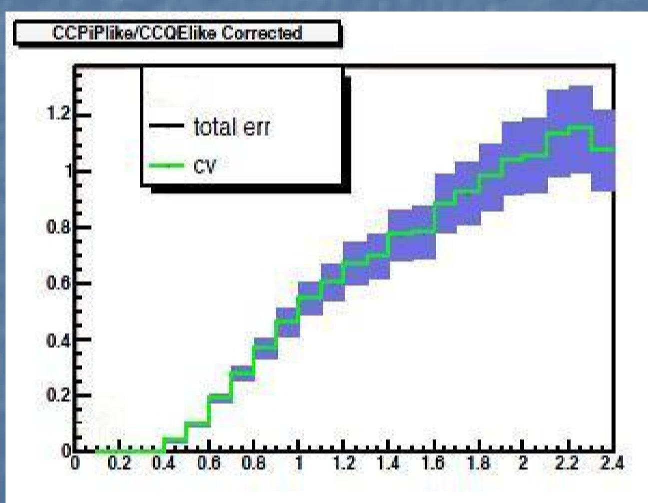
$$M_{ij}(x) = \frac{1}{s-1}\sum_{k=1}^{s}\left(N_i^k(x) - N_i^{cv}\right)\left(N_j^k(x) - N_j^{cv}\right)$$

$$\Delta N_i^{total} = \sqrt{M_{ii}}$$

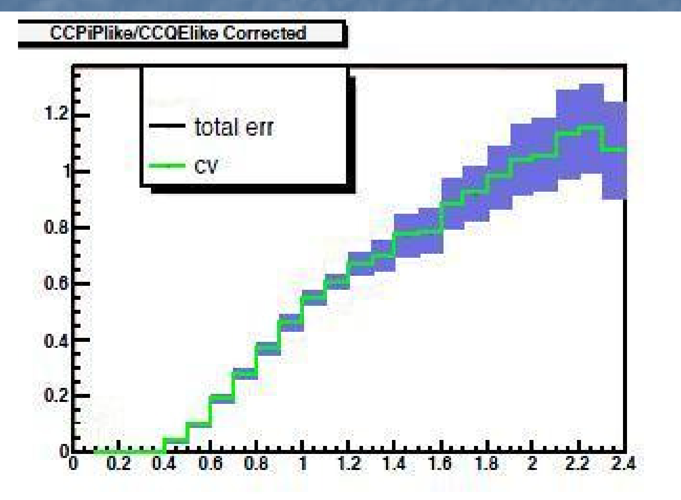
Shown are the three largest contributions to the systematic uncertainties.

Total error matrix is sum of contributions from:

π^+ production
π^- production
K^+ production
K^0 production
Beam unisim
Cross sections
π^0 yield
Optical model
Q^2 variation
Reconstruction variation
Fermi momentum variation
Unfolding matrix variation

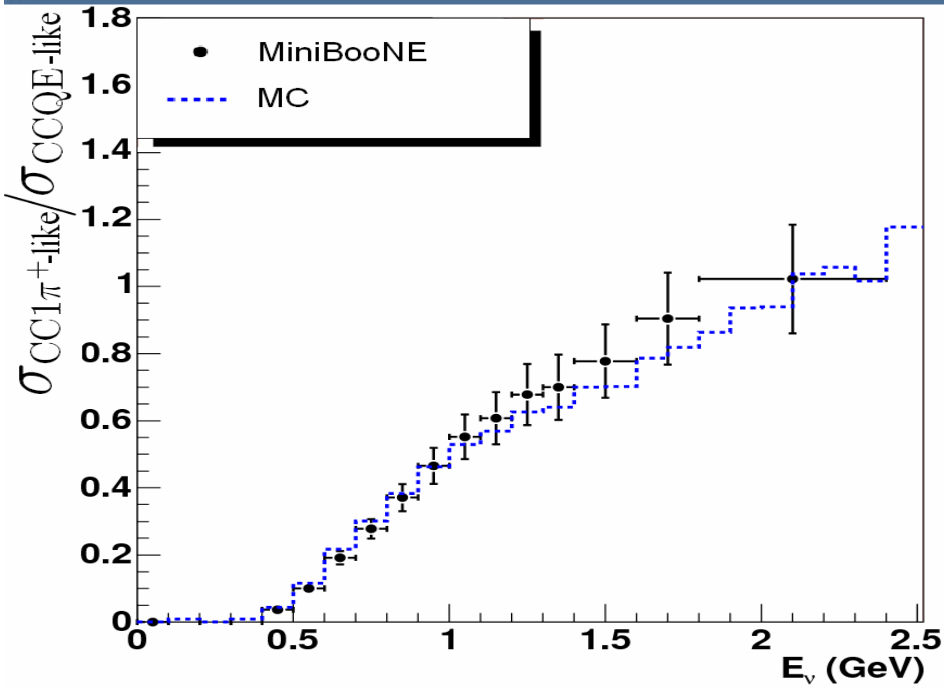


Cross sections

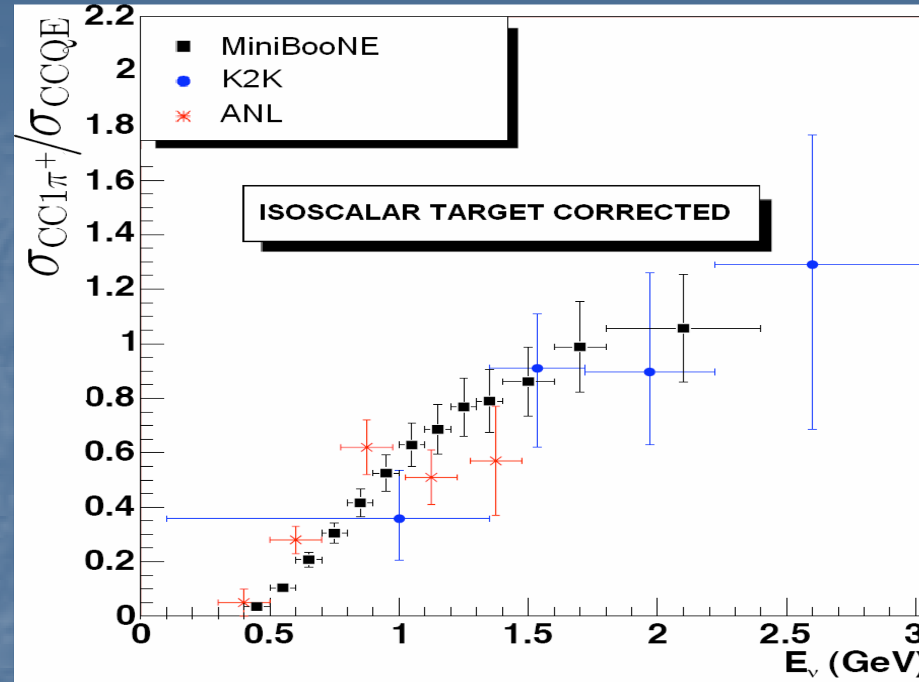


Optical model

Results



Observed Ratio



Corrected Ratio

At left: Observed ratio (without nuclear corrections) compared with Monte Carlo based on Rein-Sehgal and Smith-Moniz.

At right: Corrected ratio (with corrections for nuclear re-scattering) compared with previous measurements at ANL (1) and K2K (2).

Here the MiniBooNE and K2K ratios have been corrected for an isoscalar target (ANL's measurement was already on an isoscalar target).

(1) G.M. Radecky et al., Phys. Rev. D 25, 1161 (1982)
(2) K2K Collaboration: A. Rodriguez et al., arXiv:0805.0186

Conclusion

This is the first high-precision $CC\pi^+$ cross section measurement.

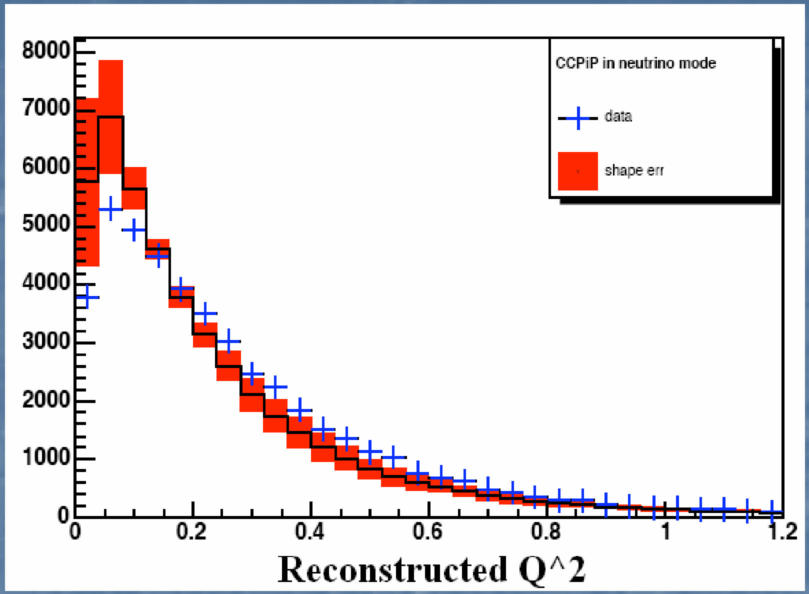
Our results are consistent with both previous experiments and predictions based on the Rein-Sehgal and Smith-Moniz models.

These results will be useful in improving pion production models, understanding nuclear effects, and constraining backgrounds to oscillation searches.

Results are in Phys. Rev. Lett. 103 081801 (2009)

Backup

Q^2 check



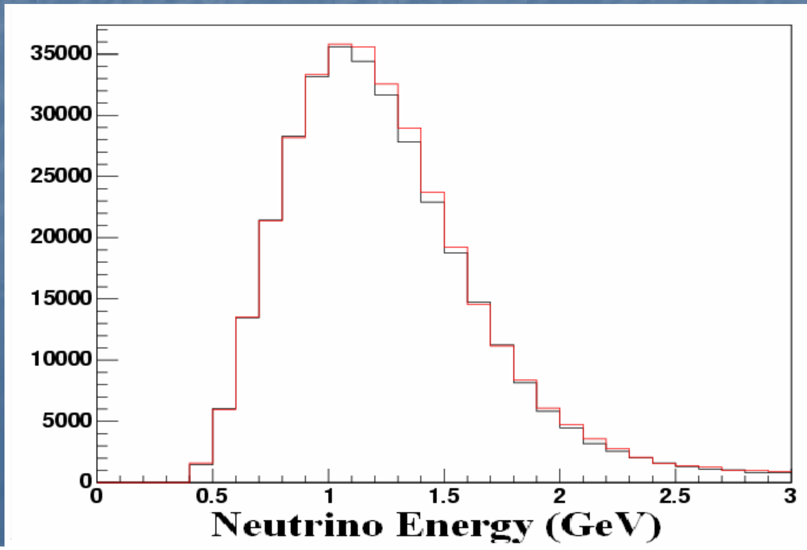
The CCPi+ sample exhibits significant data-MC disagreement at low q^2.

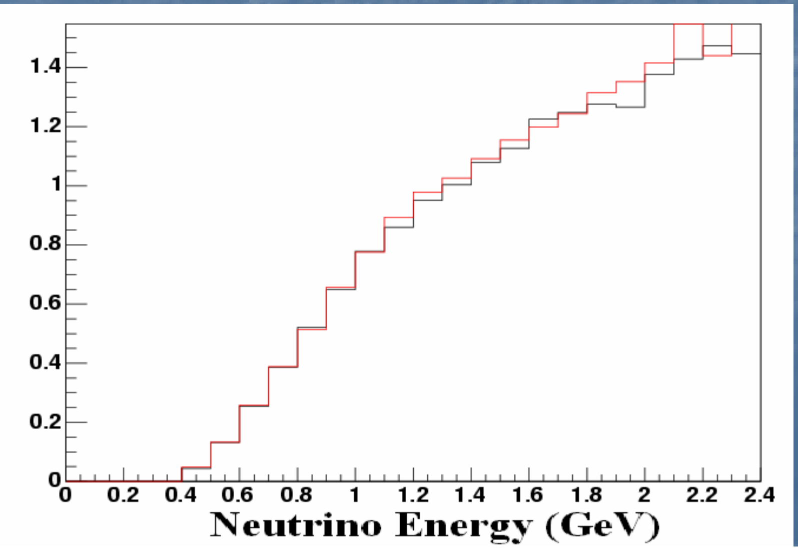
This disagreement is interesting in its own right, and J. Nowak has performed extensive studies of it in the context of improvements to the Rein-Sehgal model of pion production.

Does this disagreement have an effect on this analysis?

Checked this using a MC sample that was reweighted to agree with the data in q^2.

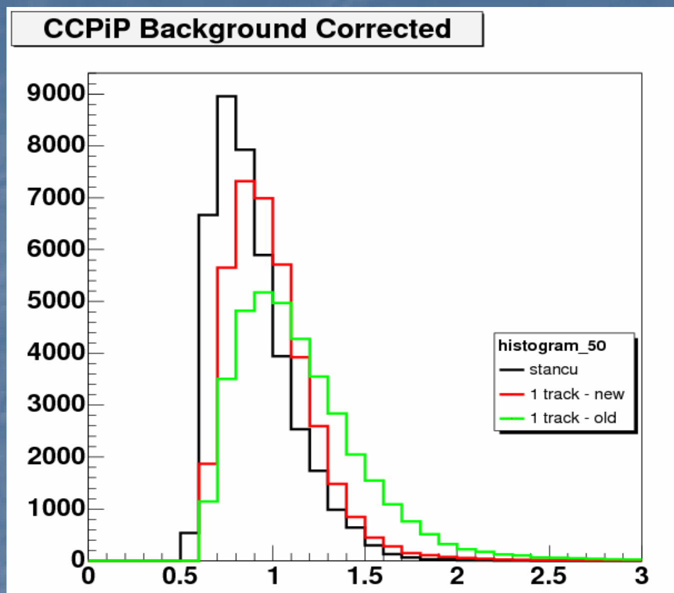
No significant effect was found; however this variation was included in the total errors.

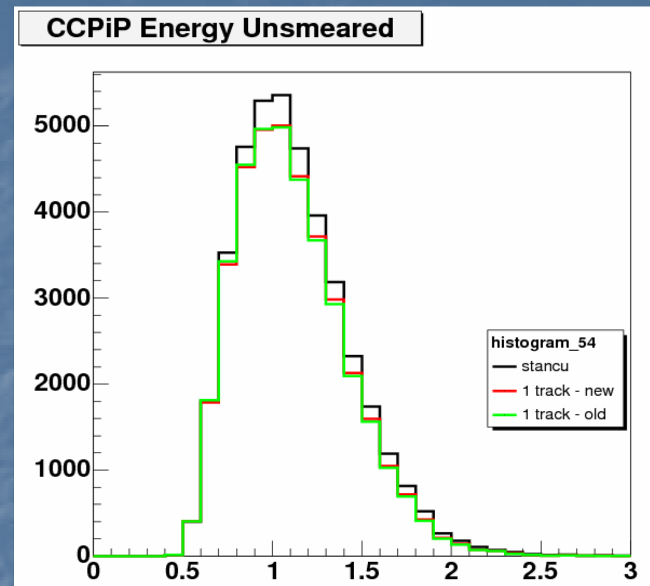


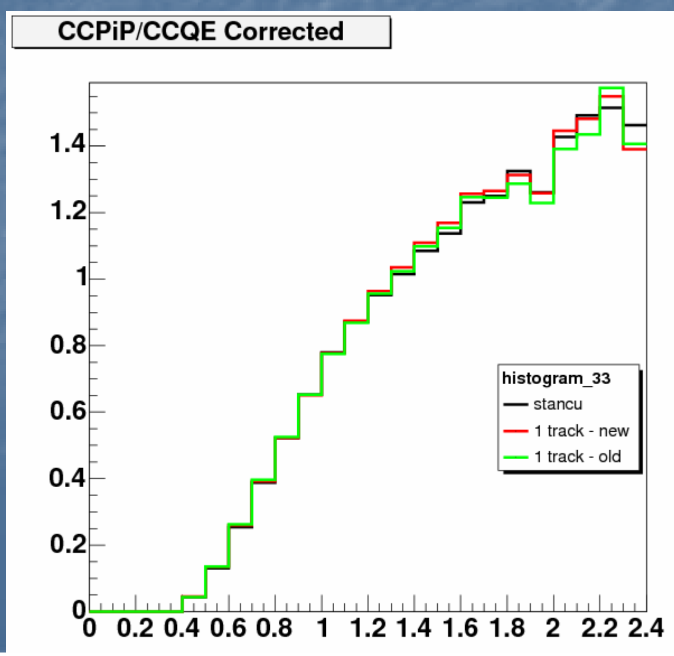


One-track Check

As a check on the principal analysis, we repeated it using a different reconstruction package:







Black = Stancu fitter
Green = One-track
Red = One-track with calibrated muon energy

Shows that the result is not very sensitive to the details of our reconstruction scheme.

Energy unsmearing seems to do its job - it corrects all three reconstructed energies back to more or less the same unsmeared distribution.

Calibration

Laser Calibration:

Pulsed diode laser sends light to four ‘flasks’ in detector.
100 ps. laser pulses peaked at 397 nm.
Flasks illuminate all PMTs with roughly equal intensity

Purpose: Measure timing and charge calibration constants for each PMT.

Cosmic Muon Calibration:

Flux of about 1 muon per cm^2 per minute
Two layers of plastic scintillator above detector
Seven scintillator cubes at various depths in tank
Provides muon trajectory, energy independent of PMTs

Purpose: Calibrate muon energy reconstruction